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These goals have been substantially accomplished. Moreover, new findings led to important discoveries that were unanticiplated at the beginning of the project. The report starts with a retrospective examination of project accomplishment. 1. Develop, implement, and enhance probabilistic model-building GAs for non-binary codes. 2. Extend existing facetwise models to non-binary codes. 3. Extend bounding test functions to non-binary code. 4. Extend the proposed non-binary algorithms to hierarchically difficult problems. 5. Apply the developed algorithms to two problems of Air Force interest.

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Final Report

# From Theory to Air Force Practice: Applications and Non-Binary Extensions of Probabilistic Model-Building Genetic Algorithms

**AFOSR Grant No. F49620-03-1-0129**
January 1, 2003 to May 31, 2006

**David E. Goldberg**
Department of Industrial & Enterprise Systems Engineering
IlliGAL Report No. X011807



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## I Objectives

The objectives of AFOSR Grant No. F49620-03-1-0129 were as follows:

1. Develop, implement, and enhance probabilistic model-building GAs for non-binary codes.
2. Extend existing facetwise models to non-binary codes.
3. Extend bounding test functions to non-binary codes.
4. Extend the proposed non-binary algorithms to hierarchically difficult problems.
5. Apply the developed algorithms to two problems of Air Force interest.

These goals have been substantially accomplished. Moreover, new findings led to important discoveries that were unanticipated at the beginning of the project. The report starts with a retrospective examination of project accomplishment.

## 2 Retrospective Examination of Accomplishment

**Efficiency enhancement from integrated model building.** A fundamental surprise was the discovery that integrating model building with various forms of efficiency enhancement results in orders of magnitude of speedup over that expected using naïve implementations. In particular endogenous fitness modeling and an adaptive continuation operator showed remarkable speedups (1-2 orders of magnitude) and a renewal proposal was prepared and has been funded to explore the extensions of these important findings.

**hBOA solves hard antenna problem for Hanscom AFB.** Scott Santarelli, Tian-Li Yu, and the PI have applied hBOA to the solution of a parameter-tuning problem in matching a Rotman lens to a Butler matrix. hBOA found a 30db-down solution when minimizing the maximum difference between main and side lobes. Even after a million function evaluations, a simple GA was unable to find an acceptable solution.

**9 orders of magnitude speed up in materials modeling.** We (Duane Johnson, Pascal Bellon, Kumara Sastry, and I) have applied genetic programming to multi-scale modeling of alloys using a hybrid of the molecular dynamics (MD) and kinetic Monte Carlo (KMC) procedures. In 2D surface modeling our calculations project speedups of 9 orders of magnitude at 300 degrees

Kelvin. Two papers have been published (*International Journal for Multiscale Computational Engineering* and *Physics Review B*). Simply stated, genetic programming is used to perform *customized statistical mechanics* by bridging the different time scales of MD and KMC quickly and well.

**Speedups in multiscaling for chemistry, too.** Work involving Todd Martinez (2005 MacArthur fellow), Duane Johnson, and the PI has applied multiobjective GAs and model building to the principled speedup of excited state direct dynamics calculations in chemistry. This work is providing fresh insights and important research avenues toward fast, accurate chemistry calculations in an array of important problem areas.

**Multiobjective hBOA scalability explored in hard multiobjective problems.** The scalability of multiobjective estimation of distribution algorithms was explored with fundamental theory and computational experiments. Depending on the number of optima that need to be tracked in each substructure, it is easy to overwhelm the capacity of all known niching algorithms due to simple combinatorial overload. On the other hand, effective niching can capably preserve a large and well spaced subset of the optimal set or it can preserve the full Pareto optimal in those cases when the optimal set grows in a manner that does not overwhelm the solver.

**Compact classifier system invented.** The idea of an estimation of distribution algorithm has become commonplace in optimization problems, but these ideas have not been widely explored in machine learning applications. First results and publications were prepared on the *compact classifier system* that uses a population of EDAs to capture a population of rules.

**BOA used to speed machine learning.** Much of the work of this project has been devoted to optimization, but first steps were made to use competent EDAs to learn effective substructure in rule-learning problem domains. In difficult hierarchical machine learning problems, the substructural identification procedures proved useful in solving extraordinarily hard classification problems quickly and well.

**From bit strings to real codes to programs.** Using mixtures of Gaussians at the subspace level, C. W. Ahn has built an effective real BOA (rBOA) that tackles problems in $R^n$ quickly, reliably, and accurately. Early competent GAs solved pseudo-boolean problems (problems over bitstrings). We recently carried those results over to the problem of scalable genetic programming, GAs that program computers. We showed that competence technique reduces exponential performance to subcubic as predicted by our experience with bitstring GAs. Experiments are underway to carry these results over to practical material science and chemistry problems. A cornerstone of the Illinois approach is to build facetwise models of critical phenomena. A key to our success in GP was building models of effective statistical decisions and population supply for GP.

**Organizationally inspired competent GA solves hierarchically difficult problems.** Techniques using dependency structure matrices (DSMs) have been used by large corporations and governmental agencies in organizational design and last year results were reported on using genetic algorithms for DSM clustering. Those results led previously to the creation of a GA called the DSMGA using DSM clustering to do building-block decomposition. A US patent

application has been filed for both the GA clustering of DSMs and the use of DSMs in the creation of a competent GA. This year, those results have led to a hierarchical version of the DSMGA that solves hierarchical difficult problems through explicit substructure compression.

**Little quantitative models of teams (and models).** The style of modeling used to advance competent GA design has led to the creation of some novel quantitative models of team size, employment frequency, and other phenomena using simple tradeoff models (decision speed vs. task speed, transaction costs versus search costs, etc.). These little models parameterize important quantities in organizations that are usually treated by qualitative means in the business literature. A paper was presented (at the Academy of Management Conference) on optimal department size in an organization with different communication rates vertically and horizontally. A recent little model optimizes the tradeoff in modeling between accurate models and those that are easily used.

**Collaborative systems software inspired by GAs.** Technical innovation in GAs has led to a spinoff project in collaborative systems design inspired by competent GA ideas. In collaboration with NCSA, I am working on a project for innovation support over the web using interactive GAs, human-based GAs, and chance discovery. The project, DISCUS or "Distributed Innovation and Scalable Collaboration in Uncertain Settings" has attracted new funding and a surprising amount of attention. A US patent application has been filed. See http://www-discus.ge.uiuc.edu/ for additional information. Work specifically in this area has been funded under the recent AFOSR IS&T BAA.

## 3 Personnel Supported

This section details the individuals supported on this project.

**Faculty supported.** Professor David E. Goldberg, the principal investigator, was supported during the summers of 2003-2005. Duane Johnson (MatSE) was partially supported during the summer of 2004.

**Other affiliated vistors postdoctoral personnel.** The following is a list of visiting faculty or postdocs affiliated with the project. Unsupported affiliates may have had some travel or incidental expenses paid by the project:

1. Professor Pier Luca Lanzi (Politecnico di Milano, Italy)
2. Dr. Xavier Llora (Ramon Llull University, Barcelona, Spain)
3. Dr. Hussein Abbass (University of New South Wales, Australian Defence Force Campus)
4. Dr. Kei Ohnishi (Kyushu University, Japan)
5. Dr. Naohiro Matsumura (Osaka University, Japan)

**Graduate student affiliates.** The following is a list of graduate students supported or affiliated with the project. Unsupported affiliates may have had some travel or incidental expenses paid by the project:

1. Chen-Ju Chao (TRECC)

2. Abhimanyu Gupta (NCASR)
3. Feipeng Li (TRECC)
4. Kazuhisa Inaba, (Tsukuba University, Japan)
5. Mohit Jolly (NCASR)
6. John Loveall (TRECC)
7. Kumara Sastry (MatSE)
8. Jai Vasanth (NCASR)
9. Paul Winward (AFOSR)
10. Tian-Li Yu (AFOSR)
11. Peng Zang (NCASR)

**Undergraduate student affiliates.** The following is a list of graduate students supported or affiliated with the project. Unsupported affiliates may have had some travel or incidental expenses paid by the project:

1. Karen Czarnecki (AFOSR)
2. Jeffrey Leesman (TRECC)
3. Ryan Spraetz (AFOSR)
4. David Ball (AFOSR)

## 4 Publications for 2003

Butz, M., D. E. Goldberg, and K. Tharakunnel. Analysis and Improvement of Fitness Exploitation in XCS: Bounding Models, Tournament Selection, and Bilateral Accuracy. *Evolutionary Computation, 11*(3), 239-277 (2003).

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Yu, T.-L., K. Sastry, and D. E. Goldberg, Online Population Size Adjusting Using Noise and Substructural Measurements. *Proceedings of the 2005 Congress on Evolutionary Computation (CEC2005)* (2005).

## 6 Publications 2006


Alías, F. X. Llorà, L. Formiga, K. Sastry, and D. E. Goldberg, Evaluation Consistency in iGAs: User Contradictions as Cycles in partial-Ordering Graphs. *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing* (ICASSP 2006), 865-868 (2006).

Butz, M.V., M. Pelikan, X. Llorà, and D. E. Goldberg, Automated Global Structure Extraction For Effective Local Building Block Processing in XCS. *Evolutionary Computation, 14*(3), 345-380 (2006).

Lanzi P.L., D. Loiacono, S. W. Wilson, and D. E. Goldberg, Classifier Prediction based on Tile Coding. *GECCO-2006: Proceedings of the Genetic and Evolutionary Computation Conference,* 1497-1504 (2006). Best paper award LCS/GBML track.

Lanzi P.L., D. Loiacono, S. W. Wilson, and D. E. Goldberg, Prediction Update Algorithms for XCSF: RLS, Kalman Filter, and Gain Adaptation. *GECCO-2006: Proceedings of the Genetic and Evolutionary Computation Conference,* 1502-1512 (2006).

Llorà, X., D. E. Goldberg, Y. Ohsawa, N. Matsumura, Y. Washida, H. Tamura, M. Yoshikawa, M. Welge, L. Auvil, D. Searsmith, K. Ohnishi, and C.-J. Chao, Innovation and creativity support via chance discovery, genetic algorithms, and data mining. *New Mathematics and Natural Computation, 2*(1), 85-100 (2006).

Llorà, X., K. Sastry, F. Alías, D. E. Goldberg, and M. Welge, Analyzing Active Interactive Genetic Algorithms using Visual Analytics [poster]. *GECCO-2006: Proceedings of the Genetic and Evolutionary Computation Conference,* 1417-1418 (2006).

Matsumura, N., D. E. Goldberg, and X. Llorà, Communication Gap Management for Fertile Community. *Journal of Soft Computing* (in press).

Pelikan, M., K. Sastry, and D. E. Goldberg, Sporadic Model Building for Efficiency Enhancement of hBOA. *GECCO-2006: Proceedings of the Genetic and Evolutionary Computation Conference,* 405-412 (2006).

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Sastry, K., P. Winward, D. E. Goldberg, and C. Lima, Fluctuating Crosstalk as a Source of Deterministic Noise and Its Effects on GA Scalability. Proceedings of the 2006 EvoWorkshops, 740-751 (2006).

Sastry, K., D. D. Johnson, A. L. Thompson, D. E. Goldberg, T. J. Martinez, J. Leiding, and J. Owens, Multiobjective Genetic Algorithms for Multiscaling Excited State Direct Dynamics in Photochemistry. *GECCO-2006: Proceedings of the Genetic and Evolutionary Computation Conference, 1745-1752* (2006). Best paper real-world applications track.

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Tsutsui, S., M. Pelikan, and D. E. Goldberg . Probabilistic Model-building Genetic Algorithms using Histogram Models in Continuous Domain. *Journal of the Information Processing Society of Japan* (in press).

Winward, P. and D. E. Goldberg, Fluctuating Crosstalk, Deterministic Noise, and GA Scalability, *GECCO-2006: Proceedings of the Genetic and Evolutionary Computation Conference,* 1361-1368 (2006).

Yu, T.-L. and D. E. Goldberg, Conquering Hierarchical Difficulty by Explicit Chunking: Substructural Chromosome Compression, *GECCO-2006: Proceedings of the Genetic and Evolutionary Computation Conference*, 1385-1392 (2006).

## 6 Interactions and Transitions

This section lists meeting participation, presentations, and transitions.

### Meetings & Presentations

All conference papers above represent presentations by Professor Goldberg, his affliates, or his students. Additionally, Professor Goldberg gave many keynote talks and tutorials during the grant period.

- EuroGP 2003, Colchester, UK, 2003 (keynote)
- Introductory Tutorials in Optimization and Search Methodologies, Nottingham, UK, 2003 (tutorial)
- 7th Joint Conference on Information Sciences, Research Triangle, NC, 2003 (keynote)
- University of Vermont Workshop on Evolutionary Computation, 2003 (keynote)
- Spencer & Spencer Systems Mathematics and Computer Science Lecture, UMSL, 2003 (invited lecture)
- GECCO-2003, Chicago, IL, 2003 (tutorial)
- ACDM Lecture, Adaptive Computing in Design and Manufacture, Bristol, UK, 2004 (keynote)
- CIRP Keynote, CIRP Design Seminar, Shanghai, China, 2005 (keynote).
- ICIP Keynote, IEEE International Conference on Image Processing, Genoa, Italy, 2005 (keynote).
- Joint Australian Conference on Artificial Intelligence & Australian Conference on Artificial Life, Keynote, Sydney, 2005.
- Frontiers of Computational Science, Keynote, 2005.

### Transitions

**Competent GA techniques transferred to Hanscom AFB.** As part of this project, hBOA and other competent GA techniques were used in concert with Hanscom AFB personnel to improve the performance of evolutionary antenna design. hBOA proved pivotal in obtaining results in a

difficult problem where simple GAs did not succeed. A 1½ short course was held in Urbana, IL for Scott Santarelli and Terry O'Donnell from Hanscom earlier this summer.

**hBOA licenses in the works.** The hierarchical Bayesian optimization algorithm is being under evaluation license for applications in stock market decision making. Test results are promising and a decision on a full license of the technology is imminent. A license of hBOA to a firm in electronic design automation is in the final stages of negotiation.

**Nextumi one-year old.** With venture capital provided by IllinoisVentures and Blue Chip Venture Capital, a ubiquitous recommendation, introduction, and personalization company called Nextumi was formed one year ago. Nextumi licensed AFOSR sponsored competent GA research (patents) to help to create consumer-adaptive technology.

**Kluwer Book Series Merges.** Due to the merger of Springer and Kluwer, the PI's series in *Genetic and Evolutionary Computation* will now be published as part of the Springer nameplate http://www.springeronline.com/sgw/cda/frontpage/0,11855,4-40109-69-33110213-0,00.html and the series will be merged with John Koza's series on Genetic Programming. A revamping of the series in line with Springer practices in the works.

## 7 New Discoveries, Inventions, or Patent Disclosures

### Discoveries & Inventions

Many of the papers above represent new inventions and discoveries.

### Patents

Five patents have been filed in connection with AF research in the recent past:

Llorà, X., Sastry, K. and D. E. Goldberg, *Methods for interactive computing,* US utility patent pending.

Pelikan, M. and D. E. Goldberg. *Method for optimizing a solution set.* US utility patent 7047169 granted (2006).

Pelikan, M, Sastry, K., and D. E. Goldberg. *Methods for efficient solution set optimization.* US utility patent pending.

Goldberg, D. E., T.-L. Yu, and A. Yassine. *Methods and program products for optimizing problem clustering*. US utility patent pending.

Goldberg, D. E., M. Welge, & X. Llora, X. *Methods and systems for collaboration, decision support, and knowledge management.* US utility patent pending.

Two additional disclosures are in preparation.

## 6 Interactions and Transitions

This section lists meeting participation, presentations, and transitions.

### Meeting Participation and Presentation

All conference papers above represent presentations by Professor Goldberg, his affliates, or his students. Additionally, Professor Goldberg gave numerous keynote talks and tutorials during 2003-2004:

### Transitions

**Competent GA techniques transferred to Hanscom AFB.** As part of this project, hBOA and other competent GA techniques were used in concert with Hanscom AFB personnel to improve the performance of evolutionary antenna design. hBOA proved pivotal in obtaining results in a difficult problem where simple GAs did not succeed.

**2 orders of magnitude faster and an order of magnitude better.** Competent GA techniques were used by the PI and two of his students in an extended consulting engagement for an Israeli company to improve optimization of cellular phone networks.

**ISGEC Evaluating SIGEVO.** The PI was founding chair (1999) of the International Society for Genetic and Evolutionary Computation. That society has been invited by the Assocation for Computing Machinery (ACM) to become a SIG (special interest group) as part of ACM. A decision whether to join or not should be reached by fall.

**Kluwer Book Series.** Due to the merger of Springer and Kluwer, the PI's series in *Genetic and Evolutionary Computation* will now be published as part of the Springer nameplate http://www.springeronline.com/sgw/cda/frontpage/0,11855,4-40109-69-33110213-0,00.html.

**Innovation course on line.** The PI's book, *The Design of Innovation,* has been turned into an eight-lecture online shortcourse (http://online.engr.uiuc.edu/shortcourses/innovation)

**Nextumi started.** With venture capital provided by IllinoisVentures and Blue Chip Venture Capital, a social networking company called Nextumi has been formed. Competent GA research will be used to create consumer-adaptive technology.

## 8 Honors and Awards

**JSD Professor.** Professor Goldberg was named Jerry S. Dobrovolny Distinguished Professor in Entrepreneurial Engineering in May 2003. The investiture was held September 23. 2003.

**ISGEC Fellow.** Professor Goldberg was named part of the inaugural class of Senior Fellows for the International Soceiety for Genetic and Evolutionary Computation.

**Other Awards.** 1985 NSF Presidential Young Investigator. 1995, Associate, Center for Advanced Study (Illinois). 1996, Wickenden Award (ASEE). 1997, Gambrinus Fellow (Dortmund).

**Student & Affiliate Honors**

**2003 CSE fellowship to Butz.** Martin Butz won a 2003-2004 Computational Science and Engineering fellowship at the UIUC for his work in anticipation and genetics-based machine learning.

**GECCO-2003 best paper.** Martin Butz and Kumara Sastry won best paper in classifier systems (LCS) at the GECCO-02003 for their paper "Tournament Selection: Stable Fitness Pressure in XCS" (with D. E. Goldberg).

**GECCO-2004 best paper nominations.** Three papers from lab members were nominated for best paper at the 2004 Genetic and Evolutionary Computation conference.

**GECCO-2005 best paper nominations.** Two papers from lab members were nominated for best paper at the 2004 Genetic and Evolutionary Computation conference.

**GECCO-2005 best papers and nominations.** Two lab papers won best paper awards in 2006.

**Silver Humie Award.** AFOSR sponsored work won a Silver Award in the Human Competitive Results competition at 2006 GECCO conference. Team members, Kumara Sastry, Duane D. Johnson, Alexis L. Thompson, David E. Goldberg, Todd J. Martinez, Jeff Leiding, and Jane Owens received a $3000 prize for their work on Multiobjective Genetic Algorithms for Multiscaling Excited-State Direct Dynamics in Photochemistry.